Piezoelectric Transformers for Space Applications

A. Vázquez Carazo*, Department of R&D Engineering, Face Electronics, LC
427 W. 35th Street, Norfolk, Virginia 23508, USA

Abstract

Piezoelectric transformers (PTs) have been successfully applied as step-up transformers for backlighting Cold Cathode Fluorescent Lamps (CCFL) used in the liquid crystal displays of notebook computers. In the last decade, the interest in PTs has evolved to a second group of applications. Worldwide companies are now investigating the use of PTs for power applications, including battery chargers, fluorescent ballasts, DC/DC converters and others. A third group of applications is now proposed by Face Electronics for use in the new generation of communication satellite and other commercial applications. This presentation introduces the ongoing research on space applications for PTs.

I. Introduction

Despite piezoelectric transformers (PTs) being invented in the late 50s, this technology did not reach commercial success until early the 90s. During this period, several companies, mainly in Japan, decided to introduce PT technology for applications requiring small size and low electromagnetic interference (EMI) signature. Since then, PTs have been used as step-up transformers for the CCFL inverter used for backlighting the liquid crystal display of notebook computers and personal digital assistants (PDA). In these applications, PTs provide i) high voltage gain ratios, ii) high power density – typically about $10W/cm^3$ -, iii) high output impedance, iv) high efficiency, and v) low EMI. Currently, PT applications for CCFL are limited to 5-8W.

In the last decade, the interest in PTs has moved toward a second group of applications beyond CCFL backlighting use. Companies in U.S., Japan, and Europe are now investigating the use of PTs for power applications, including battery chargers, linear and compact fluorescent ballasts, DC/DC converter, power supplies and others. In these applications, compared to the CCFL, the requirements include i) step-down transformers, ii) high power transformers, iii) high efficiency power conversion, iv) low output impedance, v) input to output isolation and v) low content of EMI. New topologies of PTs have been proposed to address higher levels of power conversion than those available with the classical Rosen type PTs (typically use for 5-8W with power densities of about $5\text{-}10W/cm^3$). This is the case for the laminated piezoelectric transformers, Transoner®, developed, patented and commercialized by Face Electronics. In these transformers power densities of over $40W/cm^3$ have already been reported for step-down applications.

A third group of applications has been recently proposed by Face Electronics for use in the new generation of communication satellite systems as well as space research. Among others, these applications include i) high voltage power supplies for driving Traveling Wave Tubes amplifiers used for satellite communication, and ii) high voltage igniters for controlling the ignition process of Pulsed Plasma Thrusters used for positioning the new generation of small satellites. These applications are characterized by a combination of high power and high voltage requirements (making them doubly complex), the need for high reliability and, in some cases, the ability to withstand extreme environmental conditions. This paper briefly introduces the ongoing research on space applications for PTs.

II. Satellite Industry Global Market & Tendencies. Opportunities for PTs

The field of satellite engineering is currently experiencing a radical transformation. Historically, this field has been driven by applications requiring the utmost in performance with little concern for cost or manufacturability. These systems have been primarily built for military applications, where performance for specialized use can justify higher cost. The current transformation of the field involves a dramatic shift from defense applications to those driven by the commercial and consumer sector, with an attendant shift in focus from design for performance to design for manufacturability. This transformation also entails a shift from small production volumes to mass production for the commercial market, and from a focus on performance without regard to cost to a focus on minimum cost while maintaining acceptable performance.

The launch of commercial communications satellite services in the early 1960s ushered in a new era in international telecommunications that has affected every facet of human endeavor. Today's satellites provide worldwide TV channels (24

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 JUN 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Piezoelectric Transformers for Space Applications**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of R&D Engineering, Face Electronics, LC Norfolk, Virginia 23508, USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001697, ARO-44924.1-EG-CF, International Conference on Intelligent Materials (5th)(Smart Systems & Nanotechnology)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

hours a day), global messaging services, positioning information, communications from ships and aircraft, communications to remote areas, disaster relief on land and sea, personal communications, and high-speed data services including Internet access. The demand for fixed satellite services and capacity continues to grow. Rapid deployment of private networks using very small aperture terminals (VSATs) – which interconnect widely dispersed corporate offices, manufacturing, supply, and distribution centers – has contributed to this growth. Approximately half a million VSATs [1] are in use around the world today employing a low-cost terminal with a relatively small aperture antenna (1-2 m). In the two last decades, wireless communication has emerged as one of the fasted growing services. Cellular wireless services, which have been leading the growth over the last decade, achieved cumulative annual growth rates in excess of 30 percent, with more than 200 millions subscribers worldwide. In parallel with these developments, rapid growth in Internet traffic is creating an exponential increase in the demand for transmission bandwidth. For example, use of the Internet is projected to grow from its present estimate of 100 million households to more than 300 millions households in the next few years.

Commercially speaking, three current trends are also fueling interest in satellite systems: 1) Direct-to-the-home television and direct broadcasting; 2) Wireless hand-held mobile phones; and 3) Growth in the number of personal computers used by individuals across the globe. In order to address these trends, multiple satellite constellations are the future, according to NASA, the Air Force, and commercial industry such as Iridium and Teledesic. Currently there are at least 14 distinct plans for satellite constellations (> 10 satellites), for everything from cellular phones to high speed internet. The reason is three fold: 1) higher performance by distributing functions to separate satellites; 2) reduced cost by increased manufacturing and distributing redundancy; 3) better upgradability for ever changing industries such communications and the internet. With this drive to multiple distributed constellations, satellites must be smaller, cheaper, and highly efficient. Thus, many current satellite subsystems must be miniaturized and packaged efficiently for better production.

This demand and trends in the satellite industry have motivated government agencies and civil entities to seek advanced technologies that will extend near-earth satellite capabilities and conserve their limited power, space, and weight resources, as well as meeting the demand for cost reductions. The initiatives can be divided in two groups. The first involves, alternative technologies now being considered to improve the existing satellite payloads. The major goal of this initiative is to reduce weight and save space while optimizing performance and reducing the cost of the full size satellites. The second development path, which has made progress in the past years, is the approach to smaller spacecraft, such as Micro and Nano Satellite. These smaller-sized, integrated, autonomous spacecraft require a significant revision in the technologies used for their development. Both of these initiatives represent a huge opportunity for the use of highly integrated technologies such as piezoelectric transformer designed to replace the existing magnetic transformers.

Two specific areas of R&D are projected for future generations of satellite: (a) Improvement of the performances of the amplifier used for satellite-to-earth communication, the Traveling Wave Tube Amplifier and (b) Advanced propulsion concepts to miniaturize the propulsion system in smaller-sized satellite.

III. Piezoelectric Transformers: Breakthrough technology for new generation of satellite

III.1. Initiatives on Piezoelectric Transformer Research for Space Applications

Efforts are under way to develop piezoelectric transformers (PTs) that incorporate a number of improvements over magnetic transformers as well as over prior PTs and can be adapted to the requirements of several spacecraft applications. The point of departure for these efforts is a commercial product line of PTs, Transoner®, developed and patented by Face Electronics, LC, Norfolk, Virginia. Transoner technology has overcome the power limitations of classical Rosen-type high voltage piezoelectric transformers.

Since 1996, Transoner has been considered the most promising alternative to magnetic transformers in a wide range of commercial applications including power supplies, battery chargers, fluorescent ballast, high voltage power supplies and others. Face Electronics currently is developing several commercial applications that use Transoner technology for power applications from 3 watts to 100 watts. Common requirements for these applications include small size, light weight, low EMI signature, high power density, and high efficiency.

In 2001, Face Electronics expanded its R&D strategy to space and military applications requiring high performance transformers that at the same time provide small size and low EMI. Currently, Face Electronics is a pioneer in research and development of piezoelectric based applications for the new generation of space satellite systems. Under two on-going SBIR research programs from NASA, Face Electronics is developing new piezoelectric transformers as well as applying them in two demanding areas for satellite applications:

- Improvement of the main payload of satellite communication systems, the Traveling Wave Tube, by replacing the conventional magnetic transformers with piezoelectric technology.

- Development of new integrated ignition systems for small satellite thruster by using piezoelectric transformer technology. This new piezoelectricaly controlled igniters will optimize the combustion efficiency while reducing the size of comparable systems based on magnetic or capacitive ignition.

III.2. TRANSONER®. Laminated-type Power Piezoelectric Transformer

Prior PTs, so-called Rosen-type PTs, are based on the initial idea of C. Rosen. In the middle 50s, he considered for the first time the use of acoustic energy instead of magnetic energy to perform the action of stepping-up and stepping down voltages. This type of transformers, which are manufactured with piezoelectric ceramics, are currently used in inverters for backlighting the cold-cathode fluorescent lamps in laptop computers, PDAs, digital cameras, camcorders, and other applications using liquid crystal displays. In these applications PTs show significant advantages compared to the magnetic technology, including a smaller footprint, low profile and reduced of magnetic interferences. However, a major drawback of Rosen-PTs is their limited power capability (5 to 10W, typically), and their restriction to only step-up applications. In 1996, in order to overcome these limitations, Face Electronics developed a new concept for transferring energy through acoustic waves by using laminated-type piezoelectric transformers. This technology was patented and registered under the name of Transoner® [2,3].

As in any piezoelectric transformer, Transoner PTs consist of an input section and an output section. These two sections are laminated one over the other one by their major areas. The first Transoners were developed using a radial design consisting of two single piezoelectric ceramic discs (input and output) bonded together in a "laminated-like" way (Figure 1). In this way, when the input section is connected to an AC electric voltage having the frequency of the fundamental radial resonance, the PT will vibrate in the radial direction. Due to the interface area joining both sections, the input vibration forces the output section to move in unison with the input section. Currently, this laminated concept has evolved to designs including multilayers for each section. The multilayer approach allows flexibility in input and output impedance design so it can be adapted to each specific application.

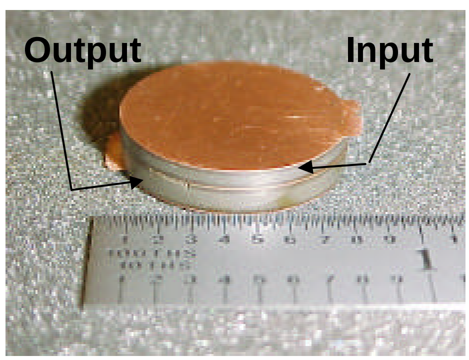


Figure 1. *Radial-type Transoner-T1*

Unlike the Rosen-type PTs, where the input and output sections are separated by a mechanical nodal section, in laminated-type piezoelectric transformer, Transoner, input and output sections vibrate completely coupled without having a nodal section separating them. Transoner laminated construction enhances the electrical to acoustic power transmission compared to prior Rosen-PTs, due to the use of a larger coupling area. As a result, higher power density levels have been demonstrated in this design. Furthermore, Transoner's laminated flexible design may be adapted to perform step-up or step-down operations, such as the ones used in AC/DC converters, battery chargers, power supplies, and other applications, and thus expanding the application possibilities of PTs.

III. Piezoelectric transformer for replacing magnetic transformers in satellite payloads

III.1. Traveling Wave Tubes (TWT) for satellite communication

TWTAs are the principal element of any public or private satellite payload for providing RF energy to carry the communications back to earth. Two parts are commonly identified in TWTAs, the electron beam tube, or TWT, and the electronic power conditioner, or EPC. The traveling-wave tube (TWT) is a vacuum device invented in the early 1940's [4] used for amplification at microwave frequencies. Amplification is obtained by transferring the kinetic energy from an electron beam to a radio frequency (RF) electromagnetic wave. Due to the nature of TWT, EPC is required to supply a number of high voltages (in the multi-kilovolt range) to drive the cathode, the multistage depressed collector, and the anode voltages. To generate these voltages, a large and fairly complex magnetic high-voltage transformer enclosed in the EPC is used. The basic components in the energy conversion chain of a satellite communication payload including the magnetic transformer are shown in Figure 2. A typical TWTA payload configuration is shown in Figure 3.

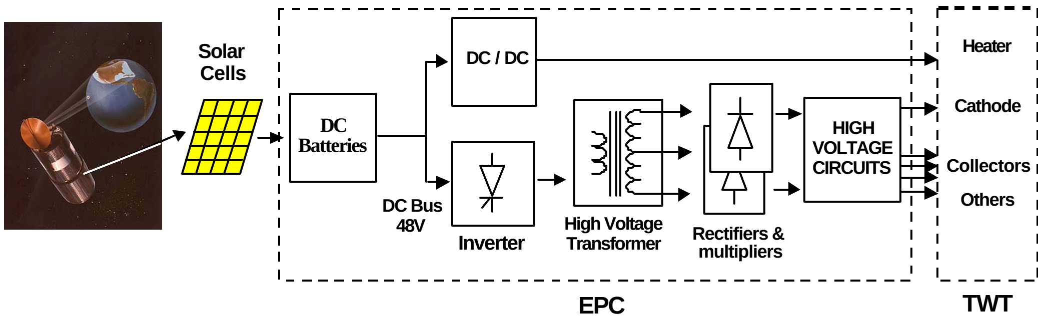


Figure 2. *Typical energy conversion in a satellite system from solar cells to TWT payloads.*

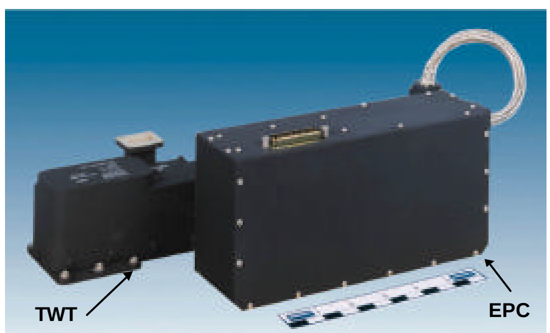


Figure 3. *Commercial TWTA payload configuration. Courtesy of Boeing-Hughes.*

A typical communications payload for TV broadcasting includes 20-100 TWTAs, each producing about 100W of RF power. The TWTAs require about 80% of the total satellite power consumption and represent about 30% of the payload mass. It is clear that any improvements in TWTA efficiency and reduction in TWTA mass will result in substantial benefits to the satellite and reductions on the overall system cost. One of the ways to improve the current state of the art of the TWTA technology is by providing a more compact and efficient EPC for driving the TWT. The reduction in size will directly allow an increase in the number of payload per satellite, and thus substantially benefit the income from renting new transponders. One of the ways to do so is by reducing the size of the high voltage transformers by replacing the current magnetic technology with more compact piezoelectric parts. This is the aim of the on-going research by Face Electronics within the scope of a Phase II SBIR NASA contract.

Conventional EPC modules for TWTs generally consist of a voltage regulated power supply that uses an electromagnetic transformer for achieving step-up requirements. The input power comes into the power module from a DC voltage bus that is generally driven from high efficiency Gallium Arsenide solar cells. An unregulated DC-bus (22 to 42V) is considered in this example. The bus-voltage is fed into the EPC through a pre-regulator (switching DC-DC converter) that converts it into a regulated constant output voltage with high efficiency, and very good regulator loop stability. Typical DC-bus voltages for satellite-based applications are in the range of 48V. An input filter is inserted between the power switch and the pre-regulator to suppress voltage ripples from the main DC-bus and switching noise from the EPC. The power converter, responsible for generating the different voltages for the TWT, is also supplied from the constant voltage V_B and generates a high frequency switching square-wave output voltage signal. Usually the switching frequency is in the range of 10kHz (old designs) to 40-50kHz. The main features of the power converter are high efficiency, avoidance of high-voltage transformer ringing, avoidance of short-circuit currents in the switching transistors, and soft recovery for the high-voltage diode. All these features are typically achieved using a push-pull [5] converter to generate a special square-voltage waveform including a definite gap time. Half and full bridge resonant inverters are also commonly used in this application. When very high DC powers (over 200W) are required, the full bridge topology is the common solution. In the conventional solution, this square signal is transformed into a several high output voltages by the high-voltage magnetic transformer [6]. A more detailed description of the internal block diagram of a typical commercial EPC is illustrated in Figure 4.

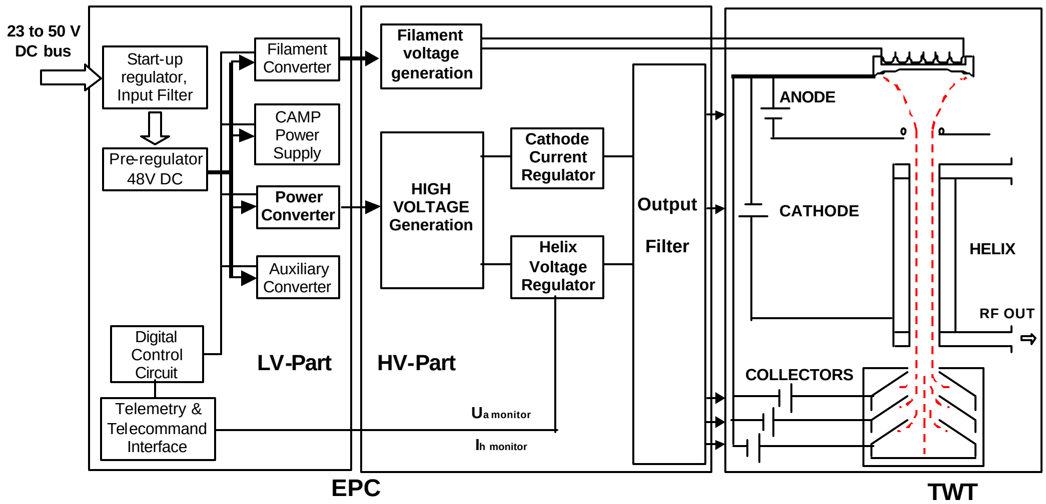


Figure 4. *Typical Block Diagram of an EPC connected to a TWT.*

III.2. Piezoelectric transformer to replace the magnetic transformer used in TWTAs

Improvement in TWT/EPC efficiency and size over the past few years has occurred in large measure from the introduction of advanced technologies including very sophisticated software modeling and optimization using proprietary computer programs. However, the electromagnetic transformer has experienced much less sophistication and remains the classical state-of-the-art magnetic technology [7]. For example, in open-air transformers (limited at lower voltages up to 10kV), this bulky, heavy, and magnetically noisy component represents about 10 to 20% of the total volume occupied by the EPC. The volume requirements can increase up to 50% of the total volume of the EPC module if large voltage epoxy-coated transformers are used. In addition, the magnetic transformer represents a large portion of the power supply mass contained within the case. Therefore, the case and other components must be shielded to protect components from the RF/EMI noise generated by the transformer, increasing size and weight of the final power module. As a result, magnetic transformers represent a significant portion of the payload volume and mass of the satellite or spacecraft TWTA.

Since several voltages must be supplied to the TWT, a typical design for the magnetic transformer consists of one primary winding and several secondary windings whose outputs are rectified and stacked to form the various collector and cathode operating potentials required by the booster TWT. Alternatively, a tapping transformer with multiple input and outputs separated by isolation layers can be used. Typically, double-stage rectifiers are used and stacked for the different output voltages including: (a) Power for electron-beam acceleration (cathode supply): This typically require the largest voltage 4 kV to 7 kV but at low cathode current (1-5mA); (b) Biasing power for collector electrodes: High voltage supplies at high power levels are required for the collector, thus representing the greatest challenge for PT technology. Typical values go from 400 V at 40W to 1.8 kV at 7.5W with respect to cathode; and (c) anode voltages. This is not a standard requirement, but some TWT require one or more anode power supplies to operate the anode at above ground potential (200V at less than 1W). The cathode to ground potential is monitored by a frequency-compensated, precision, high-voltage divider network. A cathode signal from the divider network is used to regulate the cathode voltage to the required precision (±0.5%).

Face Electronics proposal considers the use of piezoelectric transformer for replacing the high voltage magnetic transformer of the EPC. The starting point of this development is a new proposed modular design, “TAP-SONER”. This modular concept allows scaling up the performance of a single transformer. Furthermore, the modular design allows providing the different voltages and power levels required for the TWT. The same modular concept could be used for step-down applications requiring piezoelectric transformers. “TAP-SONER” is envisioned as the next step in expanding the application range of the PT technology to very high voltages and high power levels, such as those required to drive TWTs. The concept is based on adapting the Transoner basic product in a modular way that increases the power and voltage performance of the single unit. Figure 5 shows the basic approach to the "TAP-SONER" concept to be developed. The final outcome will be a significant reduction in size, weight and magnetic interferences. Other applications may include industrial lasers, medical (e.g. X-ray) equipment, spacecraft plasma thrusters, etc.

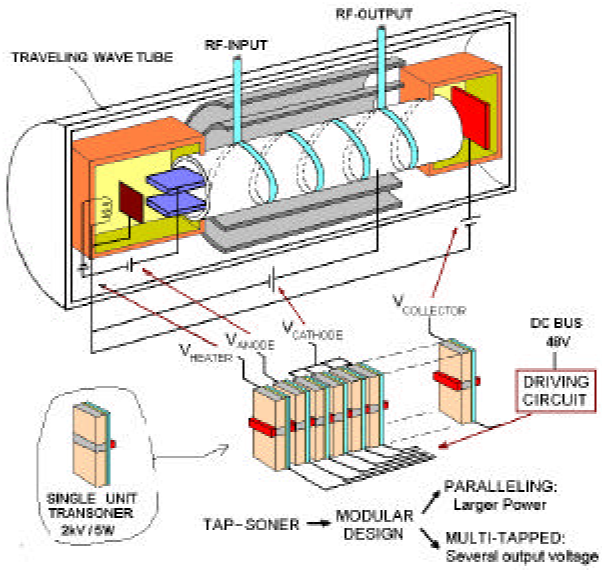


Figure 5. *"TAP-SONER" modular concept using Transoner technology applied to TWT*

The piezoelectric transformers used for this application correspond to an isolated high voltage longitudinal Transoner (Figure 6.b). This PT has been designed taking as a starting point the standard T3-Transoner of Face (Figure 6.a). The new piezoelectric transformer consists of a symmetric structure having double input sections laminated on top and bottom of the output section. The result of this symmetric design is two folds: first, the symmetric design helps to prevent the spurious bending modes that occur in the non-symmetric configuration; second, the power density is increased since the vibration of the input is coupled to the output through two interface areas.

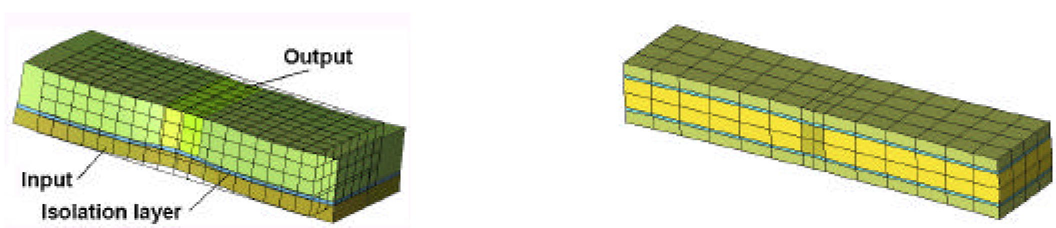
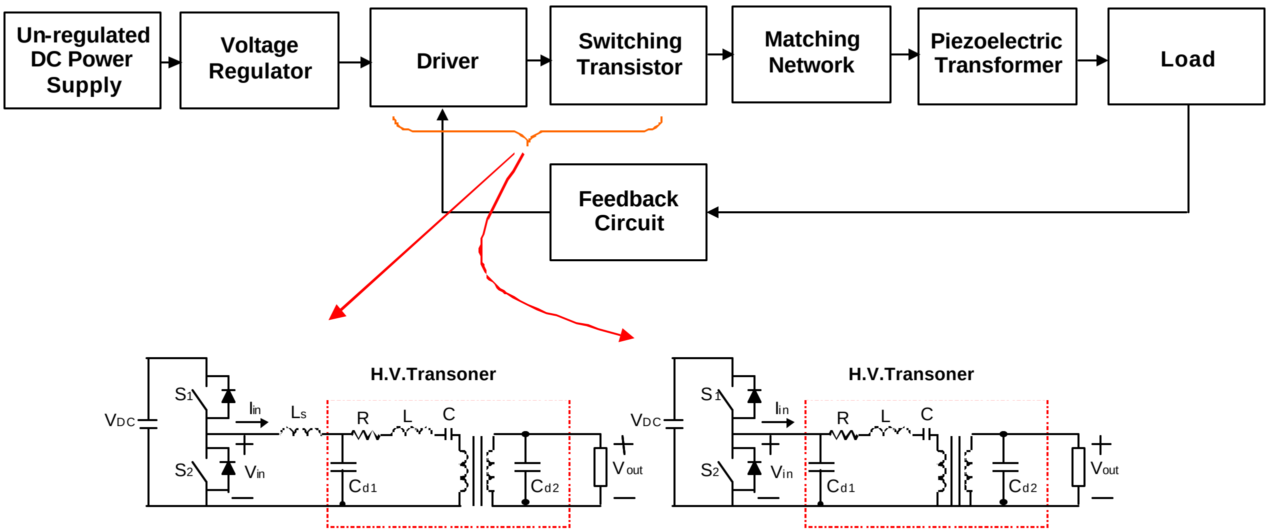


Figure 6. O*peration of the high voltage Longitudinal-type Transoner-T3 simulated using ATILA® software (by Adaptronics, Inc. for Face) (a) single input and single output section; (b) double input and single output.*

A first approach to the driving circuit is shown in Figure 7. This schematic includes the elements driving a single module of the "TAP-SONER" concept. Each module including a piezoelectric transformer will form a DC-DC converter. The DC input voltage from the 48V regulated bus voltage is converted into a high frequency switching signal to drive the input of the PT. Two different approaches are currently being considered for driving the PT: (a) The use of a series resonance to ensure the Zero Voltage Switching conditions of the switching transistors of the converter; (b) the implementation of a inductor-less circuit topology already demonstrated in the past with fluorescent piezoelectric ballast developed by Face Electronics.



Half-bridge circuit driving a Transoner and using series inductor to achieve ZVS

Proposed Inductor-less, Transoner based driving circuit

Figure 7. *"Series-inductor" and "Inductor-less" driving circuit proposed as driving circuits*

Figure 10 shows a photo of the Prototype Circuit for Inductor-less Transoner® power supply. Without any magnetic devices, the prototype circuit employs a radial vibration mode piezoelectric transformer, Transoner, as a piezoelectric transformer resonant tank for stepping up voltage.

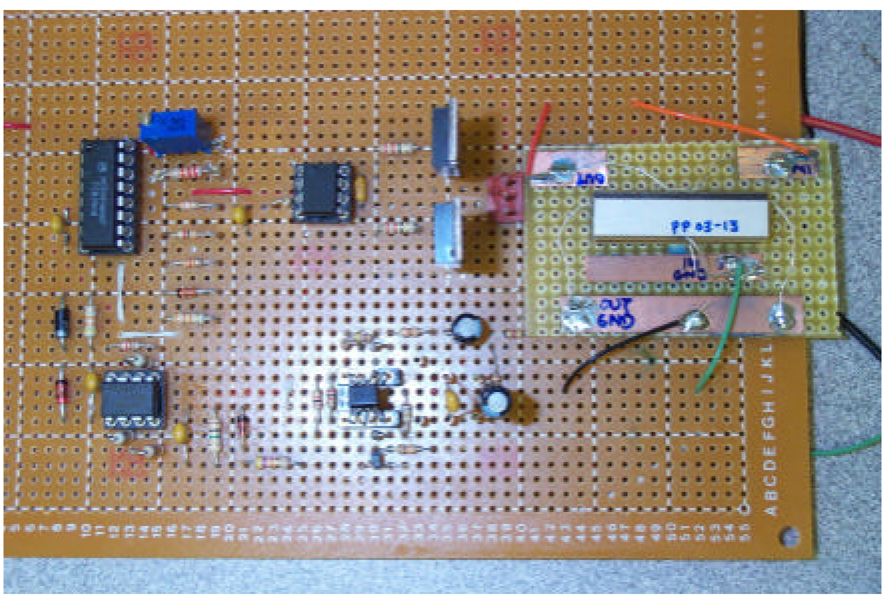


Figure 8. *Photo of the prototype circuit for inductor-less transformer power supply for a single piezoelectric transformer*

IV. Advanced Propulsions Concepts using Piezoelectric Transformers for being incorporated in "Micro" and "Nano" satellites

IV.1. Approach to the current Propulsion Systems for small spacecrafts

Multiple government agencies such as NASA and the Air Force and civil and commercial entities are developing smaller-sized, integrated, autonomous spacecraft for space missions ("Microsats" [9] weighing less than 20 kg and "Nanosats" weighing less than 1 kg). Such spacecraft will require fundamentally different approaches to propulsion than larger scale spacecraft, accounting for the unique physics occurring in physically small propulsion devices. Propulsion functions include orbit insertion, orbit maintenance, constellation maintenance, precision positioning, in-space maneuvering, and de-orbit. Propulsion technologies for spacecraft of less than 10 kg that emphasize system simplicity, low power requirements, and minimal mass are sought. These technologies, once implemented, will provide platforms with larger scientific payloads, longer-life missions, increased operational flexibility during missions, and will ultimately reduce the cost of launching payloads into orbit. Furthermore, they will also reduce the propulsion system mass for satellite orbit maintenance and attitude control will be easier to maintain for extended periods of time, and reduce the cost of Low Earth orbit (LEO) to Geosynchronous Earth orbit (GEO) orbit transfers. Advanced propulsion will also extend our ability to explore the solar system and ultimately, enable interstellar missions especially in deep space constellations, such as ST-3 [10] (formerly DS-3 mission) or Terrestrial Planet Finder (TPF), and in Earth sensing missions, such as E0-1 [11]. To accomplish these goals, innovations are needed in low thrust chemical and electric propulsion technology, including thruster components, advanced propellants, power processing units, and feed system components.

One of the most promising propulsion techniques for small satellite is the Pulsed Plasma Thursters (PPTs). PPTs have recently been proposed for primary propulsion of small spacecraft for orbit raising and life extension (attitude control, station-keeping, and primary propulsion) of low earth missions [12]. The PPT is a device in which electrical power is used to ablate, ionize, and electromagnetically accelerate atoms and molecules from a block of solid propellant material. A sample schematic of a conventional PPT system is shown in Figure 9.

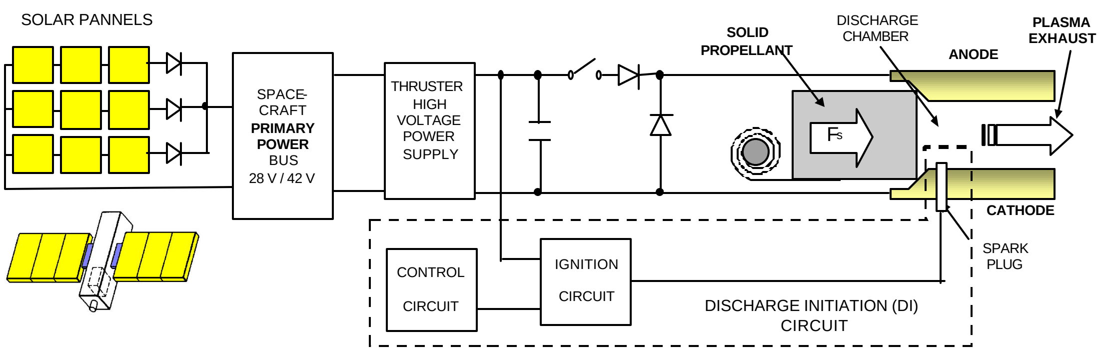


Figure 9. *Schematic diagram of the operation of a PPT*

The system includes a low DC voltage primary power supply, a high DC voltage thruster power supply, a power-processing unit (PPU), an ignition circuit, an ignition device, a capacitor, the propellant and feed system, and a thruster. The primary power supply bus is coupled to the thruster power supply, which in turn is coupled to the ignition circuit and selectively coupled to the capacitor. The ignition circuit is coupled to the ignition device, such as a spark plug, and receives commands from the control circuit. The capacitor is selectively coupleable across the thruster. In operation, the primary power supply bus provides power to the thruster power supply, which charges the capacitor to anywhere from one to one thousand joules, depending on the dimensions of the thruster. Typical values for small spacecraft are around 5 to 20 joules. The capacitor, in turn, applies this voltage across the thruster, which has two electrodes (anode and cathode) separated by a distance of typically less than 1 inch (0.25" – 0.5" are usual for small satellite). This charge places the anode at a potential of about 500 to 3000 volts above the cathode. A separate ignition device, typically a spark plug, mounted in close proximity to the propellant bar is used to initiate the arc discharge. In accordance with a signal received from the control circuit, the ignition circuit fires the ignition device. The firing of the ignition device provides a sufficient amount of energy to cause an arc to form on the surface of the solid propellant (typically polytetrafluoroethylene, PTFE or a bar of Teflon) between the thruster electrodes, thus completing the circuit with the capacitor. The electrical discharge across the spark plug produces ablation products consisting in electrons (a variety of molecular fluorocarbons) that are drawn toward the thruster anode. As the electrons are drawn to the anode, they come into contact with propellant (such as along the exposed surface of a fuel bar) causing ionization of and electron release from the propellant and initiating the main plasma arc between the thruster anode. The plasma is accelerated out of the thruster through a Lorentz force (J x B) to a velocity of 10 - 20 km/sec. The thrust generated during a single pulse is on the order of tens to hundreds of micronewtons; because the pulse duration is on the order of microseconds, the capacitor can be charged and fired several times per second producing average thrust in the micronewton to millinewton range. The low thrust per pulse results in the ability of the PPT to deliver very small impulse bits that are desirable for some precision pointing missions. The PPT plume is quasi-neutral. As the propellant surface ablates, a spring forces the propellant bar forward, providing consistent electrode/propellant geometry [13].

IV.2. Initiatives Using Piezoelectric Technology for Small Spacecraft Propulsion

Despite the very promising experience of PPTs in space and recent improvements in PPT design, there are key aspects of the PPT for which improvement would lead to significant reductions in mass, complexity and integration costs. One of such area that could hold the key to considerably more widespread usage of PPTs is in its Discharge Initiation (DI) circuit. A typical DI circuit is shows if Figure 10. It consists of a storage capacitor in the range of 1uF, a solid-state switch, an isolation transformer for the high voltage pulse, and a control circuit to control the operation of the solid state switch. In this circuit, the DI capacitor is charged from a tap off of the main power transformer. In this configuration the solid-state switch need to be specially selected due to the high voltage and currents that the switch need to turn on and off. Typically a high voltage IGBT is selected for this operation.

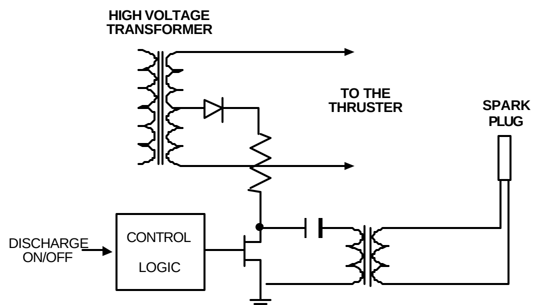


Figure 10. *DI circuit used in small spacecrafts*

This configuration is compact and acceptable for a fixed pulse energy application. However there is a limitation in spacecraft missions that need a high degree of throttle ability. Existing spark plugs as well as some of the associated high voltage equipment (e.g., insulated gate bipolar transistors (IGBT)) present particular reliability risks. In addition to unexpected failure, existing spark plugs have inherent lifetime limitations. The plugs can easily be the life-limiting component for the entire PPT system, providing less than one million pulses under some circumstances, up to a maximum proven life of ten million pulses for a known configuration. Future uses of PPTs will require twenty-forty million pulse lifetime or greater. Aside from the total failure of the spark plugs, performance decay over the functional lifetime of the spark plug can produce associated changes in thruster performance. By way of example, a new spark plug may have a breakdown voltage as low as 200 volts. Over its lifetime, the breakdown voltage will increase, for example to about 2000 volts. Another performance concern is the more random shot-to-shot variability of PPT thrust pulses. Studies have shown that much of this variability can be correlated with variability in the location of the discharge initiation spark, which, due to the annular design of existing spark plugs, is relatively wide. For smaller PPT designs the impact of this problem becomes more significant. Another problem associated with PPT's is electromagnetic interference (EMI). Studies have shown that a significant fraction of the EMI signature of a PPT is due to the spark plug event, which is comparatively high frequency phenomenon relative to the main arc discharge (further into the frequency range of concern for EMI). Another issue is weight and size. The circuitry utilized to generate the fast high voltage of the spark plug can occupy approximately one-half of the electronics board area for a PPT. By way of example, an exemplary circuit includes an 800 volts source and a 3:1 set up to achieve the necessary spark plug breakdown voltages anticipated over the plug's lifetime. These issues have been identified in previous NASA missions and are a concern to be remedied by the next generation of PPT program being conducted by NASA Glenn Research Center (GRC).

Due to the intrinsic properties of piezoelectric transformers for reaching very high voltage gains with small sizes, they become an interesting alternative for replacing the current components used in the thruster ignition system. A promising development is currently on-going by Face Electronics as part of a NASA Phase I SBIR contract. This research program proposes to demonstrate a replacement technology for use as the discharge initiation (DI) circuit of the Pulsed Plasma Thrusters (PPT) used for propulsion of spacecraft. As described above, the existing DI circuits using the capacitive discharge through a high voltage magnetic transformer is large, heavy, un-reliable, dependent on spark-plug conditions, and magnetically noisy. Face proposes a new igniting concept using piezoelectric technology for spark generation without the need for a high voltage switch, a discharge capacitor or a coupling magnetic transformer. The proposal uses the company core technology, Transoner piezoelectric transformers. The final goal of this project is to develop and integrate this technology in small size spacecraft using PPT. Through material selection, technology re-adaptation, innovative packaging, and circuit implementation, Phase I will demonstrate the use of the technology for driving a typical PPT spark plug under laboratory conditions. After Phase II's completion, the IGNIT-SONER components will be compacted in a single lightweight package, which is expected to have no electromagnetic noise, and provide high flexibility of spark control that will improve the efficiency of the ignition system. As envisioned, the IGNIT-SONER system complements the current development trend of low overall system mass and more efficient PPT for spacecraft attitude control.

Figure 11 illustrates the proposed IGNIT-SONER design, which is capable of replacing conventional magnetic-capacitive based discharge initiation transformers, the capacitive element and the solid-state high voltage switch of the currently used DI circuit of a PPT. The schematic represents the global vision of the project incorporating a Phase I "technology demonstration" and Phase II "technology integration". Phase II will focus on the integration of this technology in a compact package to be operated under spacecraft (and specifically PPT) environment conditions. Particularly, the proposed prototype for Phase I will demonstrate the capability of a piezoelectric-based ignition system device to achieve the following capabilities:

- the large voltage and power requirements for driving the ignition spark plug of a PPT under laboratory controlled conditions (*Spark generation*).
- the control of the spark timing and spark number to allow flexibility in the control of the thruster ignition as the expected final improvement of the efficiency of the ignition operation (*Spark control*)

As envisioned, a piezoelectric ignition device electrically controlled with a low voltage will be used to generate the total amount of voltage and power required for each of the propellant modules.

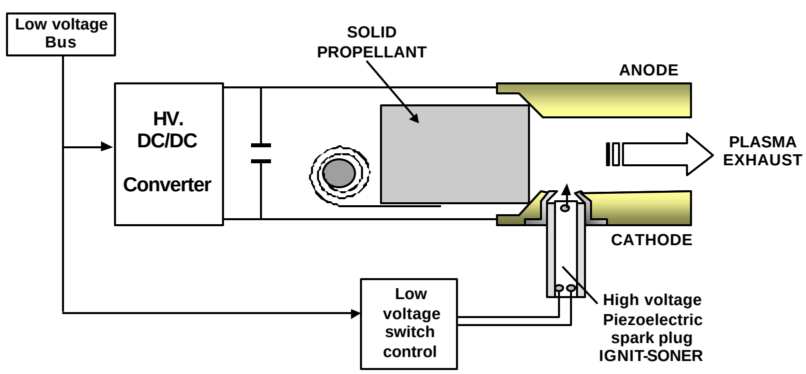


Figure 11. *IGNIT-SONER, a novel ignition system using piezoelectric technology which eliminate the discharge initiation transformer and the capacitor allowing integration, substantial reduction of weight and enhancement of the ignition efficiency*

This solution is very compact in design and will permit the complete elimination of the discharge initiation transformer as well as the discharge capacitor and the high voltage switch. Additionally, the solution is expected to be integrated in the spark plug of the thruster, thus reducing size and weight compared with the conventional solution. The solution will also eliminate electromagnetic interferences produced by currently used high voltage pulse magnetic transformers. The IGNIT-SONER discharge initiation concept is sketched in Figure 12.

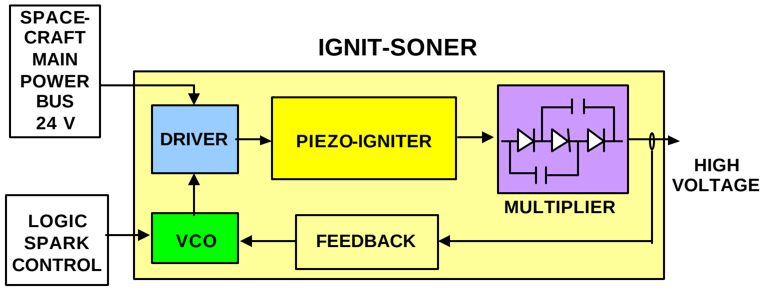


Figure 12. *Envisioned components that may be part of the IGNIT-SONER integrated ignition system with only power and control output required*

Some of the unique properties provided by this system are:

- It has inherent multi-strike capability to minimize misfire. A series of high voltage pulses may be selected from the control logic circuit as the firing strategy. These pulses may be applied, for instance, at an interval of 50-200 μs and constantly applied to the spark plug until it initiates a spark. At that point the secondary voltage decreases dramatically due to the change in the impedance of the plasma between the electrodes of the spark plug.
- It adaptively adjusts the amount of spark energy by controlling the number of pulses or the spark duration as the engine operation condition change thereby reducing plug wear.
- The alternating polarity of the spark current effectively promotes re-deposition of spark plug metal, resulting in improved plug durability. While the metal re-deposition does not offer a 100% recovery on the plug, it will extend the life of the spark plug and thus, extension of space missions.
- The solution will have minimum EMI.
- It will be able to be integrated close to the combustion chamber and thus eliminating external components such as magnetic transformer and discharge capacitor, thus having compact size and lightweight.
- It is easily controllable with an external low voltage logic control circuit.

V. Conclusions

The field of satellite engineering is currently experiencing a radical transformation. In order to match the current demands on cost reduction in satellites multiple government and civil entities are taken several initiatives to reduce weight and save space while optimizing performance and reducing cost in the existing payloads in standard satellite as well as in the future generation of smallest satellite, such as Micro and Nano Satellite. Under two on-going SBIR research programs granted by NASA, Face Electronics has become the pioneer in applying piezoelectric transformer technology to spacecraft systems. A significant change in the way piezoelectric transformers could be used in spacecraft has been introduced in this paper. In addition, an overview of the current research programs on this field has been described, including:

- Improvement of the main payload of satellite communication systems, the Traveling Wave Tube, by replacing the conventional magnetic transformers with piezoelectric technology.

- Development of new integrated ignition systems for small satellite thruster by using piezoelectric transformer technology. These new piezoelectricaly controlled igniters will optimize the combustion efficiency while reducing the side of comparable systems based on magnetic-capacitive systems.

VI. References

[1] J.Evans, Network interoperability meets multimedia, *Satellite Communication,* 30-36, February 2000.

[2] US5834882, Multilayer Piezoelectric Transformer, Richard P. Bishop, assigned to Face International Corp, Nov. 10, 1998.

[3] US2003/006752, Multilayer Piezoelectric Transformer, Alfredo Vazquez Carazo, assigned to Face International Corp, Apr. 10, 2003.

[4] US2300052, *Electron Discharge Device System*, Neils E. Lindenblad, Port Jefferson, assigned to Radio Corporation of America, Oct. 27, 1942.

[5] A.N.Curren et al., *The Cassini mission Ka-band TWT*, Electron Devices Meeting, 1994, Technical Digest., International, pp. 783-786 (1994).

[6] S.D.Johnson, A.E. Witulski, R.W.Erickson, *Comparison of Resonant Topologies in High-Voltage DC Applications*, IEEE Trans. on Aerospace and Electronic Systems, Vol. 24, No. 3, May 1998.

[7] M.A. Pérez, C. Blanco, M. Rico and F.F. Linera, *A New Topology for High Voltage, High Frequency Transformers*, IEEE INTELEC'90, 1990.

[8] Hansen, J.W., Multiple output supplies must meet TWT demands, Microwaves, **21**, pp. 198, Jul 1982

[9] Brill, Y., Eisner, A., and Osborn, L., The flight Application of a Pulsed Plasma Microthruster. The NOVA satellite, AIAA-82-1956, Nov. 1982.

[10] Cassady, R. J., Willey, M. J., Meckel, N. J., and Blandino, J. J., *Pulsed Plasma Thruster for the New Milenium Space Interferometer Experiment DS-3*, AIAA-98-3326, July 1998.

[11] Benson, S. W., Arrington, L. A, Hoskins, W. A, Meckel, N. J., *Development of a PPT for the E0-1 Spacecraft*, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-99-2276, 20-24 June 1999.

[12] LeDuc, J.R., Bromaghim, D.R., Peterson, T.T., Pencil, E.J., Arrington, L.A., Hoskins, W.A., Meckel, N.J., and Cassady, R.J., *Mission Planning, Harware Development and Ground Testing for the Pulsed Plasma Thruster (PPT) Flight Demonstration on MightySat II.1*, AIAA-97-2779, July 1997.

[13] Burton, R. L., and Turchi, P. J., *Pulsed Plasma Thruster*, Journal of Spacecraft and Rockets, Vol. 14, No. 5, 1998, pp. 716-735